SEARCHES FOR LOW-MASS HIGGS AND DARK BOSONS AT *BABAR*

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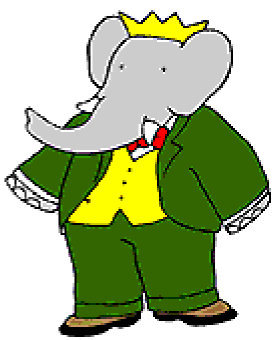
Introduction

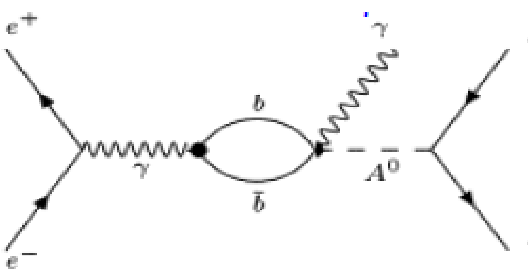
- The Standard Model scenario suffers from quadratic divergences and several models have been suggested to solve the problem
- In these models additional fields are introduced, and low-mass Higgs' bosons (in the GeV/c^2 mass range), and gauge bosons, are possible
- The search for such particles can be fruitfully exploited at low-energy/high luminosity e^+e^- machines (ex. B factories)
  - Constraints on parameter space can help understanding the most recent experimental observation of SM Higgs' boson
- BaBar is pursuing a complete program to search for such states in several decay modes (leptons, hadrons, invisible) in
  - radiative decays of Υ(nS) resonances (Wilczek)
  - Higgs-strahlung (and pair production) processes from e^+e^-

SEARCHES FOR LOW-MASS HIGGS



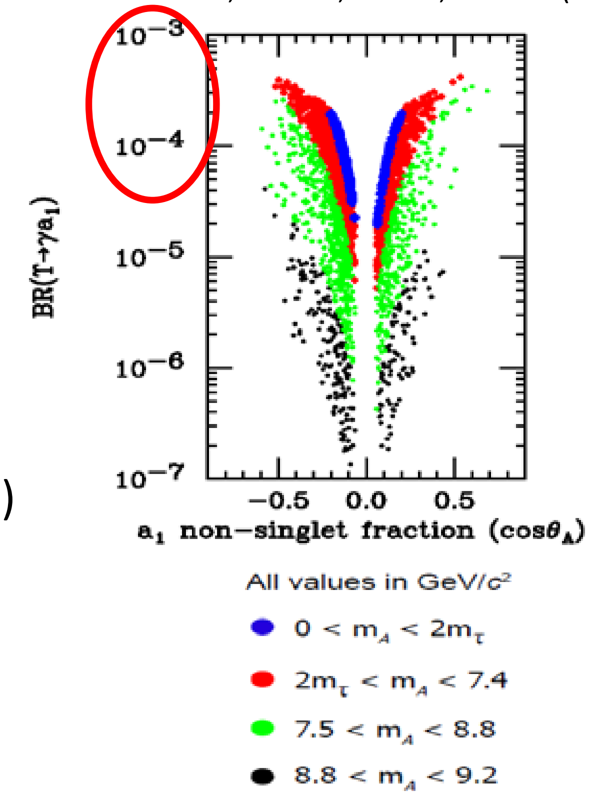
Theoretical motivations

- Among the models which include the possibility of a light Higgs: NMSSM
  - Solves the hierarchy problem
  - Adds to MSSM a total of 2 CP-odd + 3 CP-even + 2 charged Higgs
  - Lightest CP-odd Higgs (A^0): mixing of a singlet CP-odd singlet Higgs' field and the CP-odd scalar doublet of MSSM:
    - $A^0 = \cos\theta_A\, a_{MSSM} + \sin\theta_A\, a_{SM}$
  - **Lightest Higgs: mass < $2m_b$**
  - Production: radiative decays $\Upsilon(nS) \to \gamma A^0$ (n=1,2,3)



can have large branching fractions, up to 10^{-3}

Dermisek, Gunion, PRD81, 075003 (2010)



  - A^0 decays: into $f\bar{f}$ with BF depending on $\tan\beta$ and m_{A^0}

$$\boxed{BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 / \tan^2\beta}$$

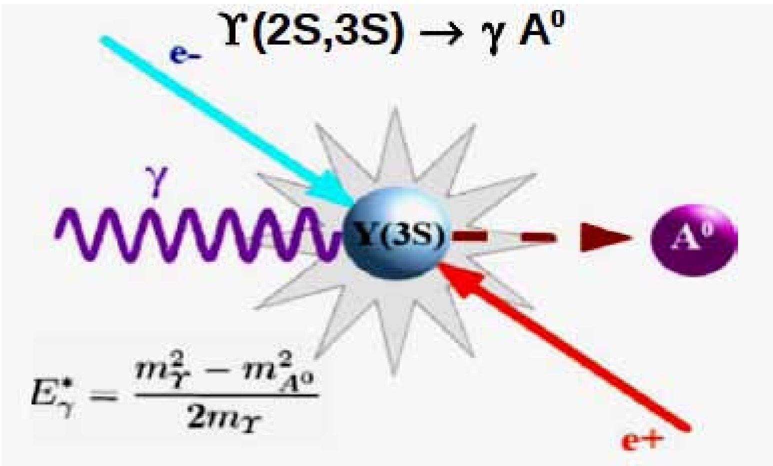
$$\boxed{BR(A^0 \to f\bar{f}) \propto \cos\theta_A m_f^2 \tan^2\beta}$$

Up-type fermions: u, c, t, ν_e, ν_μ, ν_τ

Down-type fermions: d, s, b, e, μ, τ

A^0 searches at BaBar

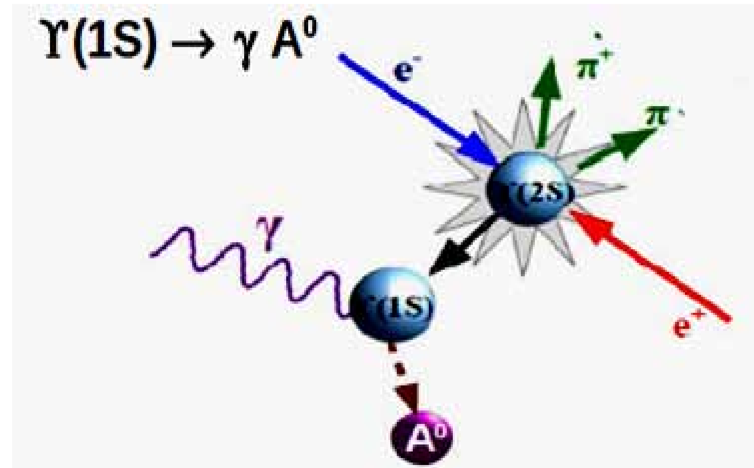
- **$\Upsilon(2S,3S)$ radiative decays**



– Search for a monochromatic photon in the recoil mass spectrum
  - $\Upsilon(2S,3S) \to \gamma A^0; A^0 \to \mu^+\mu^-$ PRL103, 081803 (2009)
  - $\Upsilon(3S) \to \gamma A^0; A^0 \to \tau^+\tau^-$ PRL103, 181801 (2009)
  - $\Upsilon(2S,3S) \to \gamma A^0; A^0 \to$ hadrons PRL107, 221803 (2011)
  - $\Upsilon(2S,3S) \to \gamma A^0; A^0 \to$ invisible arXiv: 0808.0017

Method: scan as a function of m_{A_0} of its production×decay yield by means of extended unbinned likelihood fits

- **$\Upsilon(1S)$ radiative decays**



– $\Upsilon(1S)$ selected by tagging the dipion in $\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$ transitions
– Less background, reduced using missing mass and dipion recoil mass
– Monochromatic photon in $\Upsilon(1S)$ rest frame
  - $\Upsilon(1S) \to \gamma A^0; A^0 \to$ invisible PRL107, 021804 (2011)

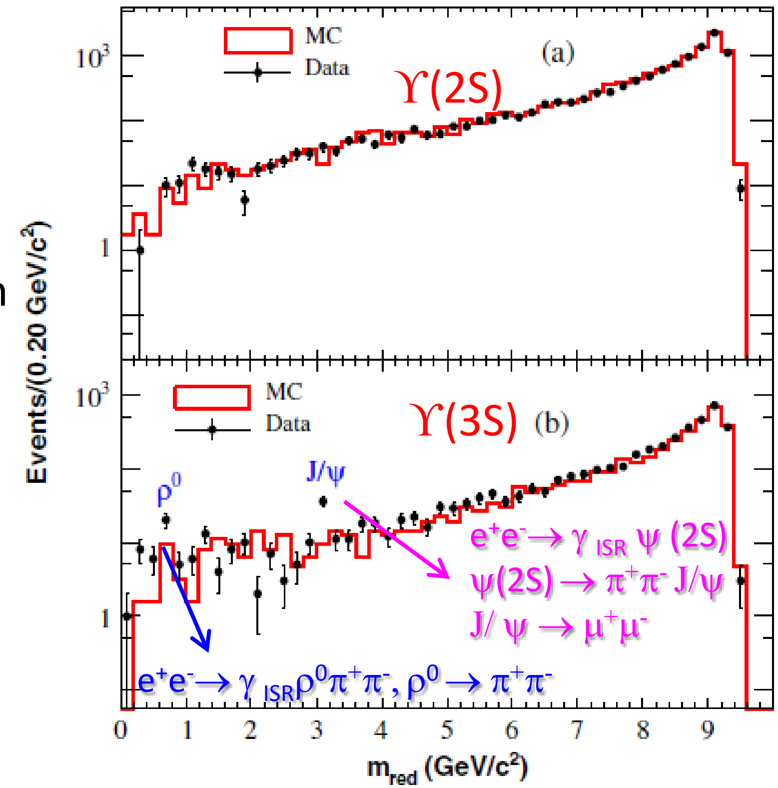
This talk

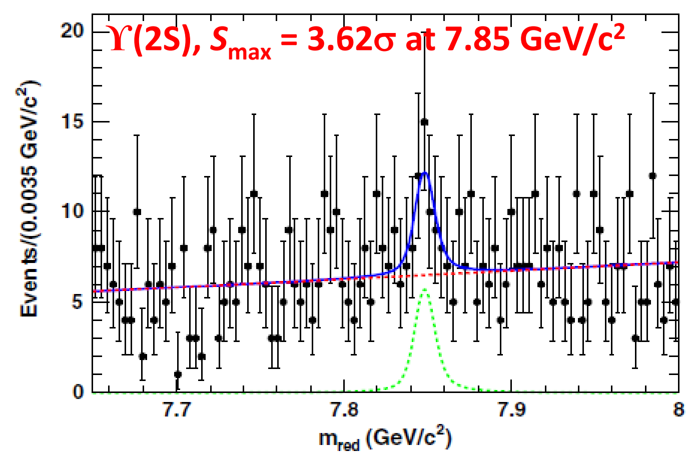
  - $\Upsilon(1S) \to \gamma A^0; A^0 \to \mu^+\mu^-$ PRD87, 031102 (2013)
  - $\Upsilon(1S) \to \gamma A^0; A^0 \to \tau^+\tau^-$ arXiv:1210.5669 accepted by PRD-RC
  - $\Upsilon(1S) \to \gamma A^0; A^0 \to gg$ or $s\bar{s}$ PRD88, 031701 (2013)

$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

PRD87, 031102 (2013)

- Substantial background reduction as compared to $\Upsilon(2S,3S)$ direct rad. decays
- Sample: 93M $\Upsilon(3S)$ + 117M $\Upsilon(2S)$
- Selection: one photon E* > 200 MeV + 4 charged tracks: at least one μ + dipion from $\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$
  - Additional soft γ's accepted, E* < 200 MeV
  - All tracks from same vertex (e^+e^- IP)
  - Beam-energy constraints on $\Upsilon(2S,3S)$
    - improve A^0 resolution (2-9 MeV/c^2)
- Backgrounds:
  - Continuum: QED $e^+e^- \to \mu^+\mu^-$
  - Peaking: ISR production of ρ^0, $\psi(2S)$ and J/ψ (only in $\Upsilon(3S)$ sample) $\Rightarrow$ J/ψ excluded
- Yield extracted from $m_R = \sqrt{m^2_{\mu\mu} - 4m^2_{\mu}}$
  - Max significance:
    - $\Upsilon(2S)$: $S = 3.62\sigma$ @ 7.85 GeV/c^2
    - $\Upsilon(3S)$: $S = 2.97\sigma$ @ 3.78 GeV/c^2
    - **Combined: $S = 3.24\sigma$ @ 3.88 GeV/c^2**
    - **Compatible with null hypothesis**





$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

PRD87, 031102 (2013)

- 90% C.L. Bayesian upper limits in the range
  $0.212 \le m_{A^0} \le 9.20$ GeV/c²
  - For the combined dataset:

$$\boxed{B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to \mu^+\mu^-) = (0.29 - 9.7) \times 10^{-6}}$$

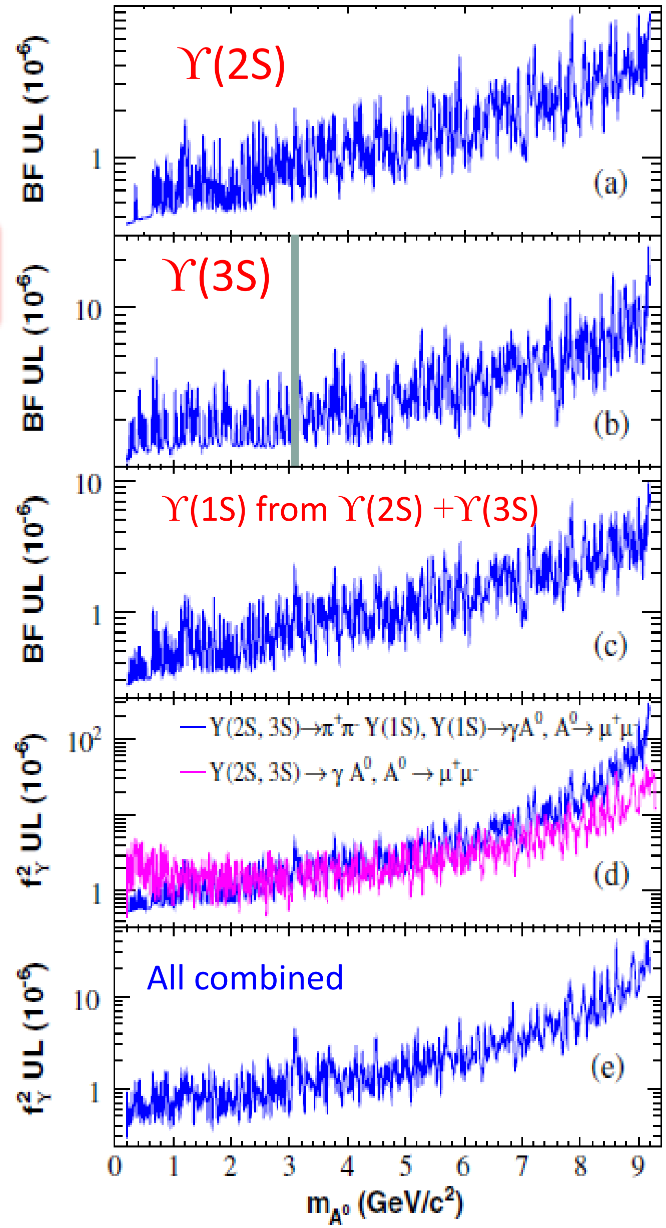
  - **Improvement of a factor 2-3 of the previous limits for $m_{A^0} < 1.2$ GeV/c²**
  - Comparable to former BaBar results for $1.20 \le m_{A^0} \le 3.6$ GeV/c² (PRD103,081803(2009))

- Can be combined with direct Υ(2S, 3S) results to set a limit to the *effective* Yukawa Higgs-b quark coupling:

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(ns)}^2}\right)$$

- For $m_{A^0} \le 9.20$ GeV/c² :

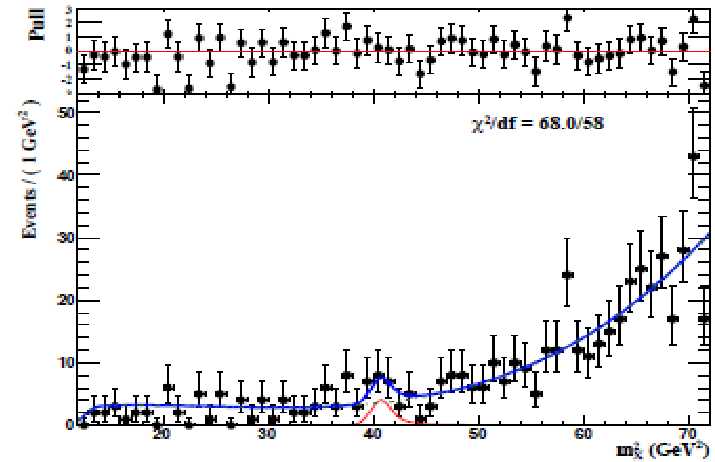
$$\boxed{f_\Upsilon^2 \times B(A^0 \to \mu^+\mu^-) = (0.29 - 40) \times 10^{-6}}$$



$\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

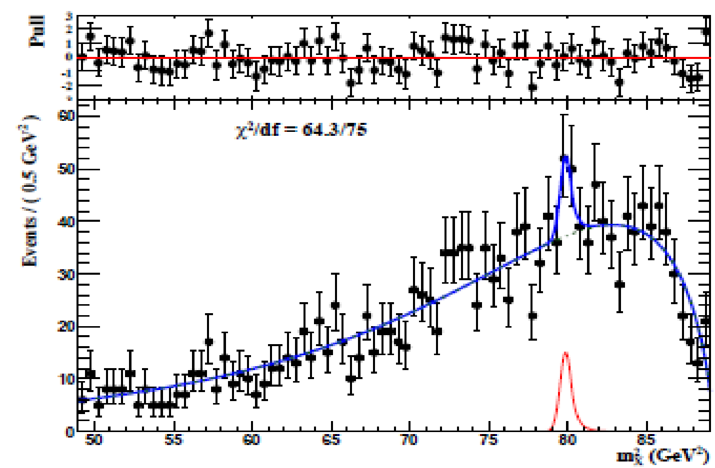
arXiv:1210.5669 (2012), accepted by PRD-RC

- Sample: 98M $\Upsilon(2S)$
- Selection: one photon E* > 200 MeV + 4 charged tracks: at least one lepton (τ decay, 5 combinations) + tagging dipion
  - Additional soft γ's accepted, E* > 30 MeV
- Backgrounds:
  - Continuum: QED $e^+e^- \rightarrow \gamma\tau^+\tau^-$ + 2γ events
  - Peaking: radiative leptonic $\Upsilon(1S)$ decays



(a)

- Yield extracted from recoil mass of the dipion system ($\Upsilon(1S)$) and missing mass ($\Upsilon(1S)$ - γ):
  - Scan range in two intervals with different optimizations:
    - $3.6 \leq m_{A0} \leq 8$ GeV/c^2 (Low)
    - $8.0 \leq m_{A0} \leq 9.2$ GeV/c^2 (High)
  - Max significance:
    - $S = 2.7\sigma$ @ 6.36 GeV/c^2
    - $S = 3.0\sigma$ @ 8.93 GeV/c^2
    - **No significant signal observed**



(b)

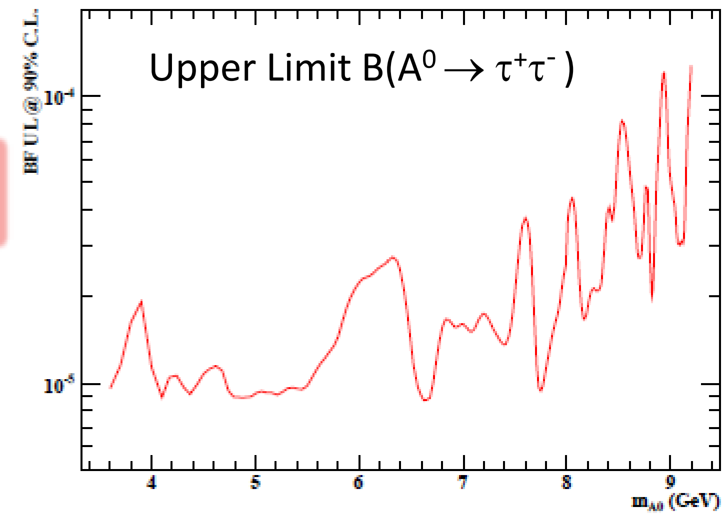
7.5% of pseudo-experiments have a >3σ fluctuation

$\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

arXiv:1210.5669 (2012), accepted by PRD-RC

- 90% C.L. Bayesian upper limit in the range $3.6 \le m_{A0} \le 9.2$ GeV/c^2

$$\boxed{B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to \tau^+\tau^-) = (0.9 - 13) \times 10^{-5}}$$

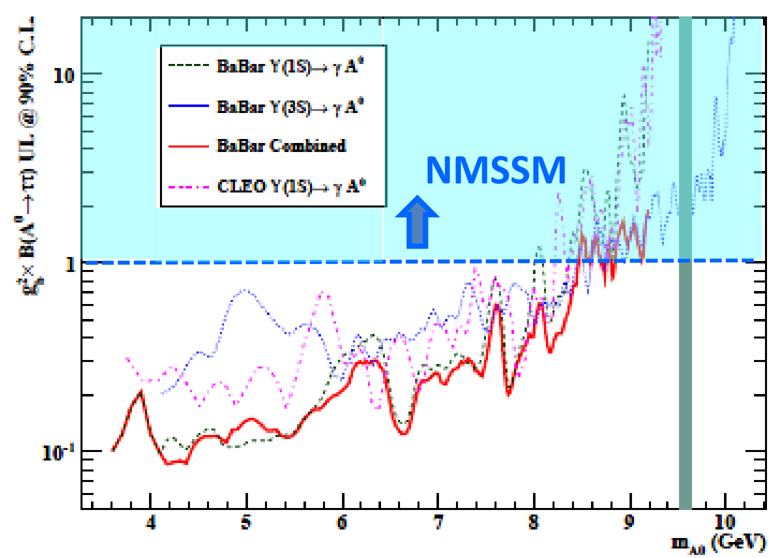


- Combined with $\Upsilon(3S)$ results to set a limit to the Yukawa Higgs-b quark coupling:

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{g_b^2 G_F m_b^2}{\sqrt{2\pi\alpha}} \mathcal{F}_{QCD} \left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

- For $m_{A0} \le 9.2$ GeV/c^2 :

$$\boxed{g_b^2 \times B(A^0 \to \tau^+\tau^-) = (0.09 - 1.9)}$$



$g_b = \tan\beta \cos\theta_A \Rightarrow$ much of the parameter space preferred by NSSM (>1) is ruled out

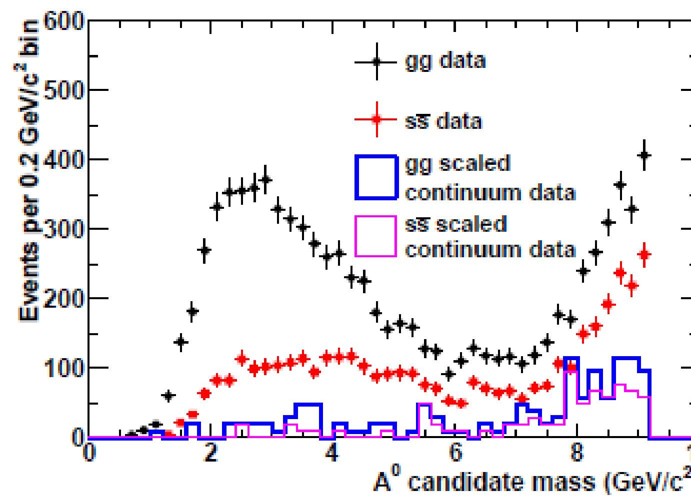
$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg, s\bar{s}$

PRD88, 031701 (2013)

- Sample: 122M $\Upsilon(3S)$ + 99M $\Upsilon(2S)$
- Selection: one photon E* > 200 MeV + 2 charged tracks (dipion from $\Upsilon(2S)$ transitions) + hadronic system from A^0 decay products (26 reactions)
  - PID of K, π, p ($s\bar{s}$: reactions with at least 2K)
  - A^0 reconstruction: exclude 2-body FS
    - A CP-odd Higgs cannot decay in 2 pseudoscalars
  - Beam-energy constraints on $\Upsilon(2S)$

#	Channel	#	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K^0_S\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K^0_S\pi^\mp\pi^+\pi^-2\pi^0$
7	$3\pi^+3\pi^-$	20	$K^+K^-2\pi^+2\pi^-\pi^0$
8	$2\pi^+2\pi^-\eta$	21	$K^+K^-2\pi^+2\pi^-2\pi^0$
9	$3\pi^+3\pi^-2\pi^0$	22	$K^\pm K^0_S\pi^\mp 2\pi^+2\pi^-\pi^0$
10	$4\pi^+4\pi^-$	23	$K^+K^-3\pi^+3\pi^-$
11	$K^+K^-\pi^0$	24	$2K^+2K^-$
12	$K^\pm K^0_S\pi^\mp$	25	$p\bar{p}\pi^0$
13	$K^+K^-2\pi^0$	26	$p\bar{p}\pi^+\pi^-$

- Backgrounds:
  - $\Upsilon(1S) \to ggg$, $\to \gamma gg$ with gluon hadronization
- Yield extracted from background subtracted mass spectrum
  - Range: $0.5 < m_{A^0} < 9$ GeV/c^2
  - Largest upward fluctuations:
    - gg: 2.7σ @ 8.13 GeV/c^2
    - $s\bar{s}$: 3.2σ @ 8.63 GeV/c^2



$\Upsilon(2S,3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A^0 \to gg, s\bar{s}$

PRD88, 031701 (2013)

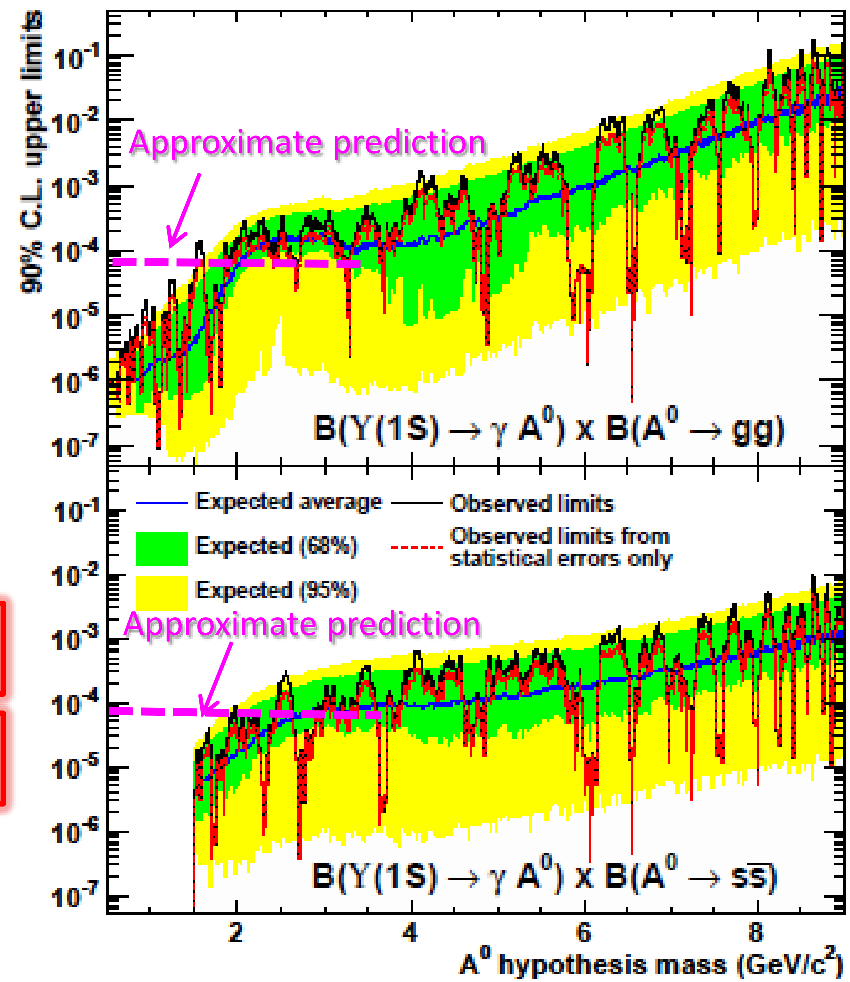
- How often such a statistical fluctuation can occur in simulated experiments:
  - gg: 86%
  - $s\bar{s}$: 59%
  - **No evidence for A^0 signal in the hadronic mass spectra, nor other hadronic resonances**

- 90% C.L. Bayesian upper limits in the range $0.5 < m_{A^0} < 9.\ \mathrm{GeV}/c^2$

$$B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to gg) = 10^{-6} - 10^{-2}$$

$$B(\Upsilon(1S) \to \gamma A^0) \times B(A^0 \to s\bar{s}) = 10^{-5} - 10^{-3}$$

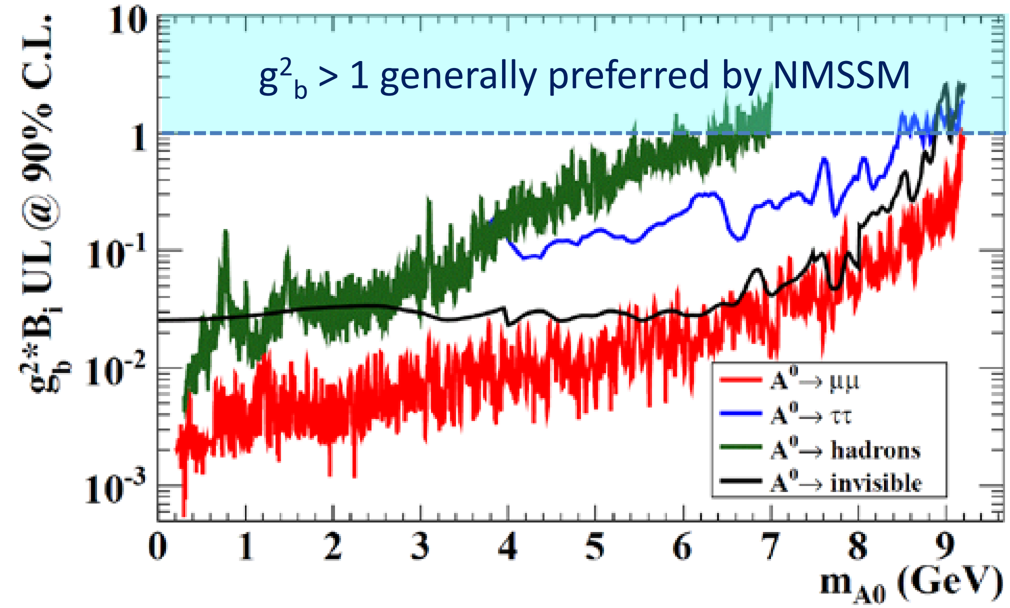
The limits are less stringent than what obtained in the leptonic decays

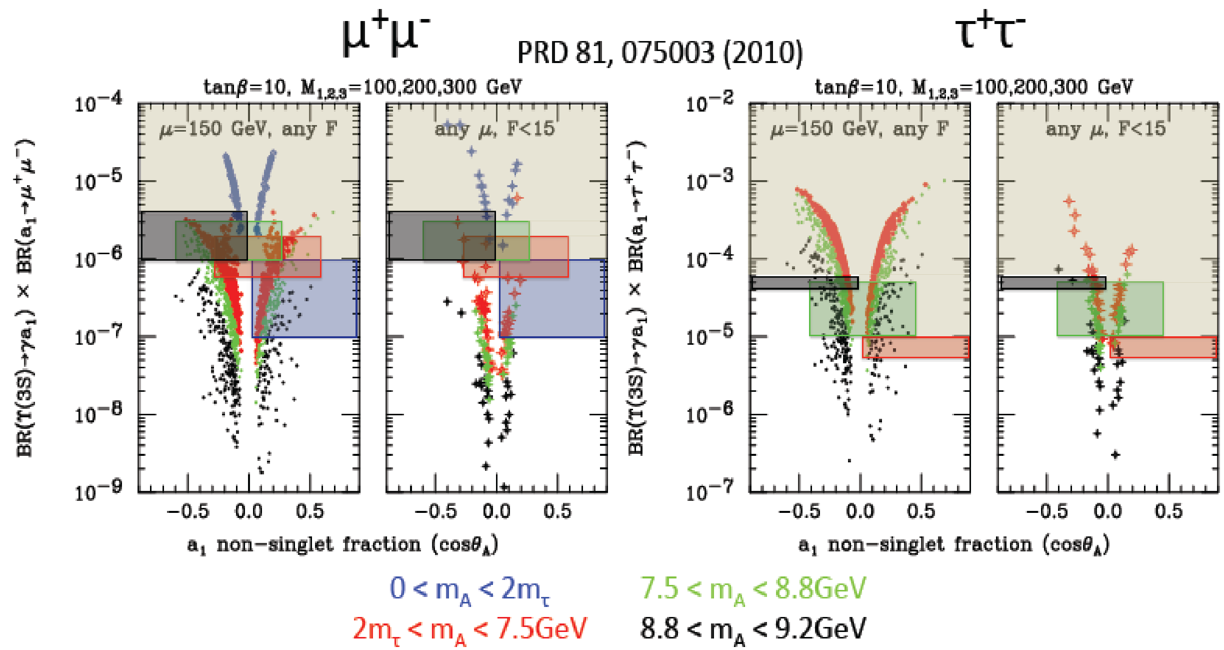


Parameter space excluded by the data

- Upper limits for A^0 coupling to b-quarks from several Babar measurements

  ($g_b = \cos\theta_A \tan\beta$)

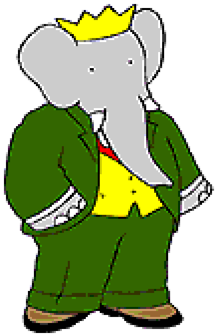




The boxes indicate the ranges permitted by the experimental measurements for different massed

- The space above the upper edge of the boxes is excluded
- Strong constraints on the parameter space

SEARCHES FOR DARK BOSONS

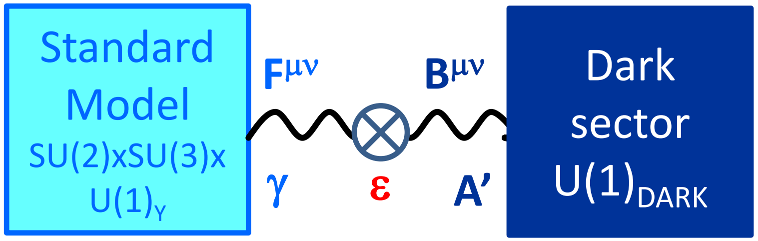


TM & © Nelvana

Dark sector gauge bosons: search motivations

- Several clear experimental evidences for the existence of Dark Matter from terrestrial and satellite experiments
  - PAMELA, INTEGRAL, ATIC, DAMA/LIBRA, CREST, HESS, …
    - 511 keV photon flux from the Galactic center (1-10 MeV e^+/e^- source?)
    - Positron and electron fluxes (NO protons/antiprotons!)
    - Annual modulation signal

- These (+null) results can be thoroughly interpreted resorting to a new hidden $U(1)_{DARK}$ gauge group which couples to $U(1)_Y$
  - Kinetic mixing of dark matter particles to SM ones through a dark photon: $\varepsilon F^{\mu\nu} B_{\mu\nu}$
    - Small coupling ε
    - Typical range: $10^{-6} \leq \varepsilon \leq 10^{-2}$
    - Gauge bosons produced in DM annihilation



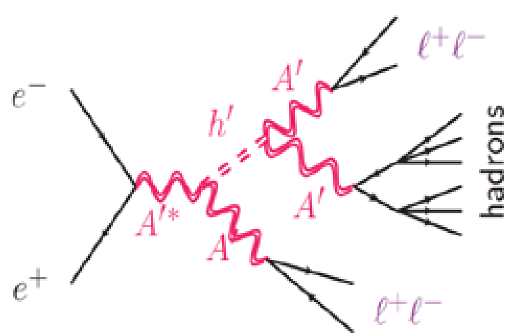
  - Massive dark photon A' generated via Higgs' mechanism (dark Higgs h' added to the theory)
    - Expected mass: at most few GeV/c^2, if coming from TeV/c^2 mass DM
    - Observable at B factories: low background environment

Dark sector gauge bosons: signatures

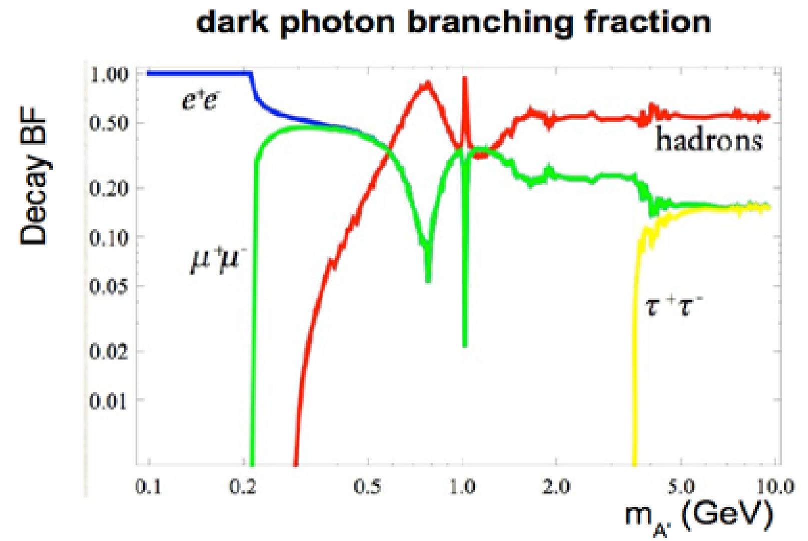
- Through the kinetic coupling the dark photon A' gets an effective charge by which it couples to SM fermions
  - Coupling strength: $\alpha' = \alpha\varepsilon^2$
  - Large coupling to electrons and muons at low masses

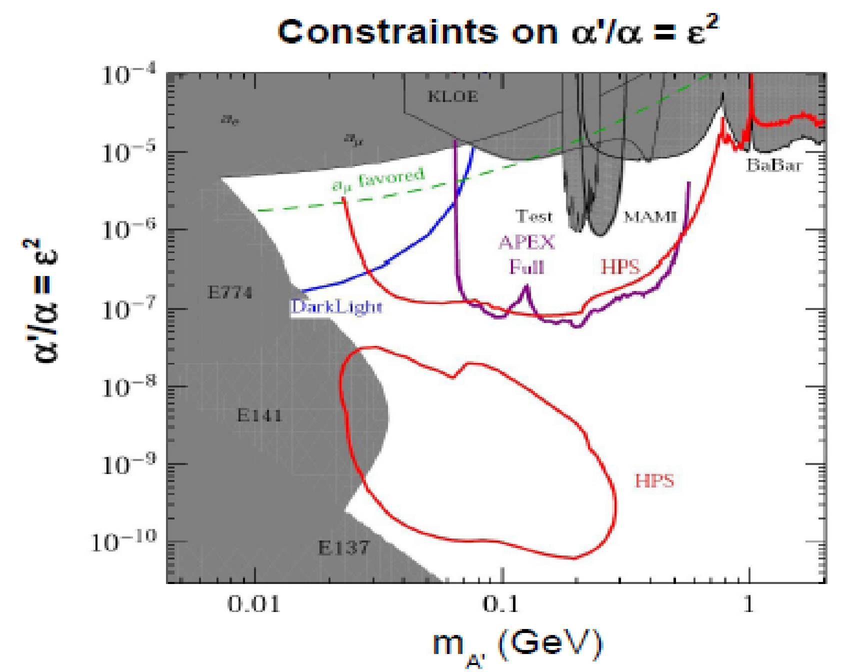
- Light dark-Higgs boson
  - Decays into 2 dark bosons
  - $m_{h'} > 2\, m_{A'}$: prompt decay
  - $m_{h'} < m_{A'}$: prompt or displaced
  - Higgs' production: Higgs-strahlung

    $e^+e^- \rightarrow A'h',\ h' \rightarrow A'A'$



Batell et al, PRD79, 115008 (2009)

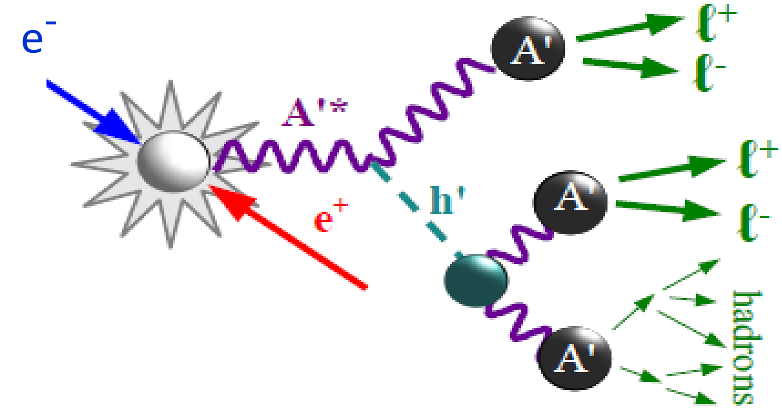


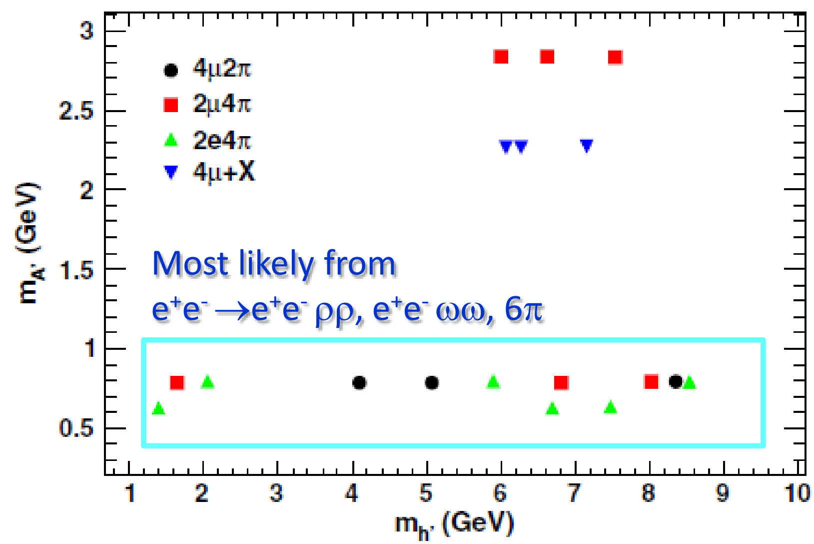


Bjorken et al, PRD80, 075018 (2009)

Dark Higgs searches at BaBar PRL108, 211801 (2012)

- Higgs-strahlung:
  - only suppressed by one power in ε
- Constraint: $m_{h'} > 2\, m_{A'}$
- Ranges:
  - $0.8 \leq m_{h'} \leq 10$ GeV/c^2
  - $0.25 \leq m_{A'} \leq 3$ GeV/c^2
- Data: full dataset, 516 fb^{-1}
- Selection:
  - Exclusive mode: 6 fermions in pairs of opposite charge/flavor
    - Full reconstruction of the 3A’
      - similar masses
      - e^+e^- c.m. energy constraint
      - Same vertex (IP)
  - Inclusive mode: 2 lepton pairs for A’ + X
    - 2 similar masses for A’
    - 3rd A’ from missing mass
- Background: wrong sign combinations
- **6 events found (each: 3 entries)**





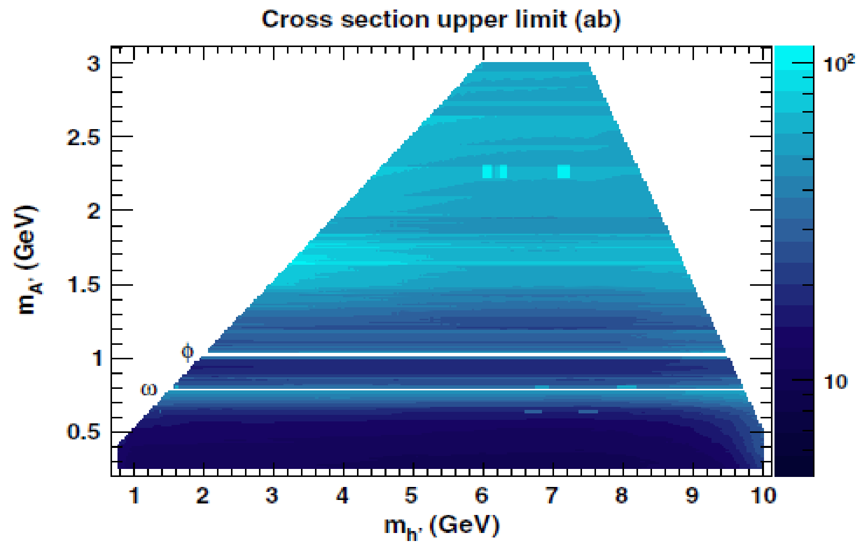
No event by 6 leptons

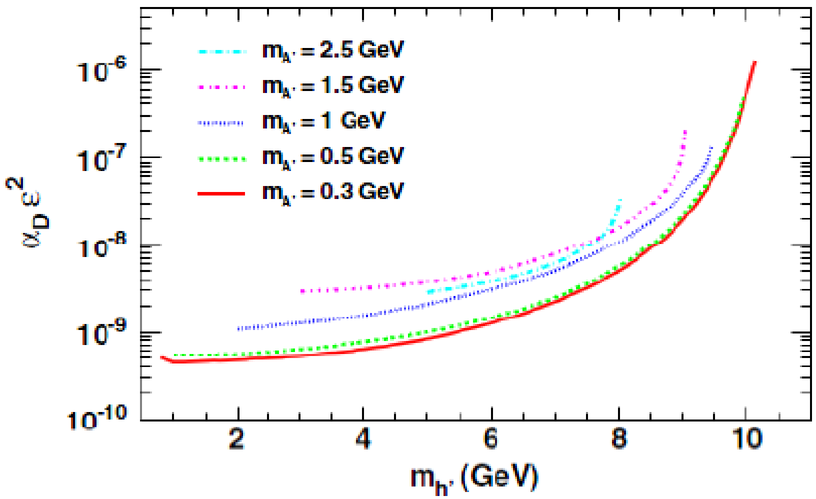
Signal consistent with background

Dark Higgs searches at BaBar

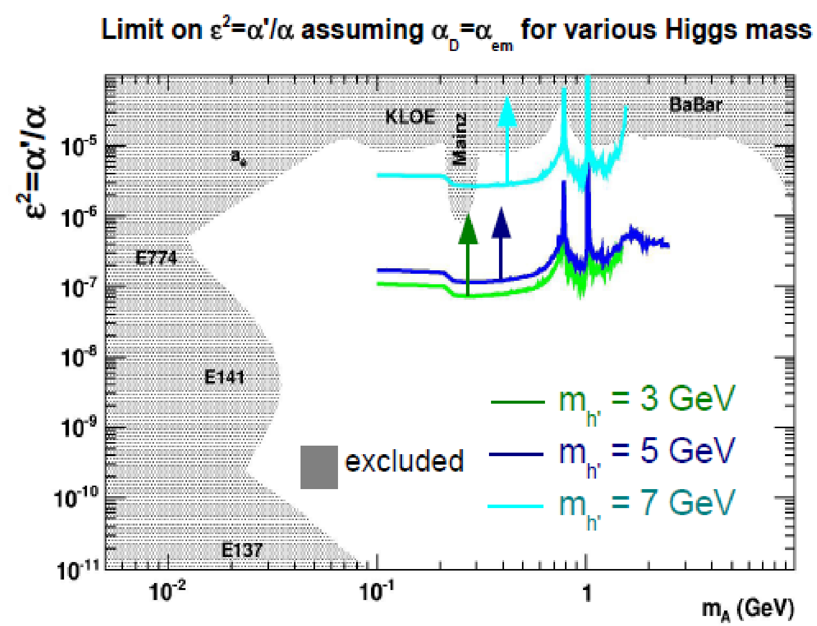
PRL108, 211801 (2012)

- 90% C.L. Bayesian upper limit on the **production cross section: (10-100) ab**
- 90% C.L Bayesian upper limit on $\alpha'\varepsilon^2$ as a function of $m_{h'}$ and $m_{A'}$: **10^{-10}-10^{-8}**

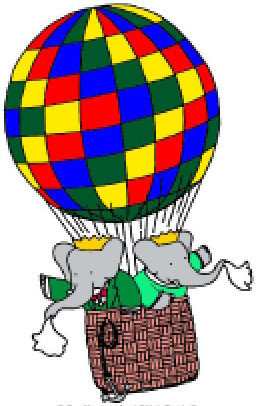




- $\alpha' = \alpha$: limits on the mixing strength ε^2
  - **10^{-4}-10^{-3}**
  - One order of magnitude smaller than current bounds
    - substantial improvement if a light dark Higgs (< 5-7 GeV/c^2) exists



CONCLUSIONS

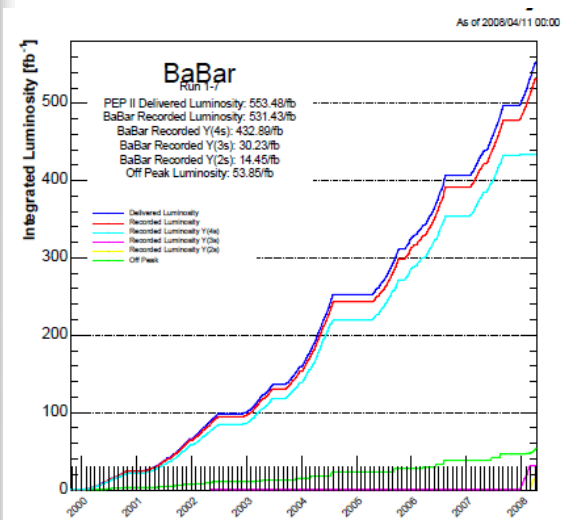


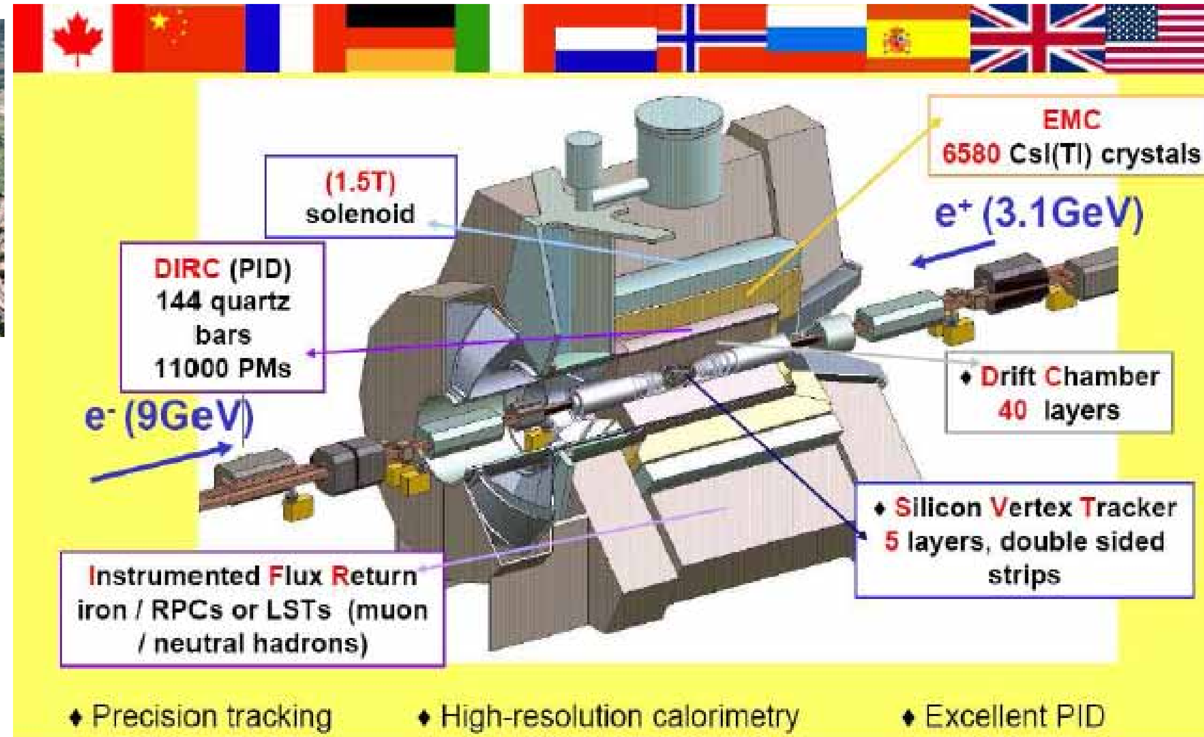
Summary and outlook

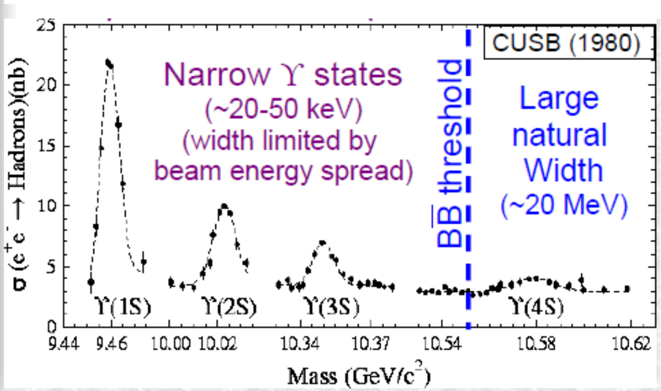
- Low energy e^+e^- colliders provide a clean environment to look for MeV-GeV Higgs' and dark sector bosons
- BaBar searched for evidence of two kinds of light Higgs' particles:
  - Light Higgs favored by NMSSM
    - Comprehensive searches using a variety of Υ(nS) decay channels
    - Significant constraints on NMSSM parameter space
  - Dark Higgs (and gauge bosons) suggested by dark sector models
    - Searches for signals from Higgs-strahlung
    - Constraints on the coupling parameters
  - No evidence observed so far
    - Upper limits O(10^{-6}-10^{-5}) on cascade branching fractions
  - Further searches still in progress
    - A^0 decaying in $\gamma\gamma$, $c\bar{c}$
    - Dark photon: $e^+e^- \to \gamma A'$; $A' \to e^+e^-$, $\mu^+\mu^-$, hadrons, invisible

BACKUP SLIDES

The BaBar experiment at PEP-II, SLAC







PEP-II and BaBar operated from Oct 1999 to Apr 2008, ~ 500 fb^{-1} integrated

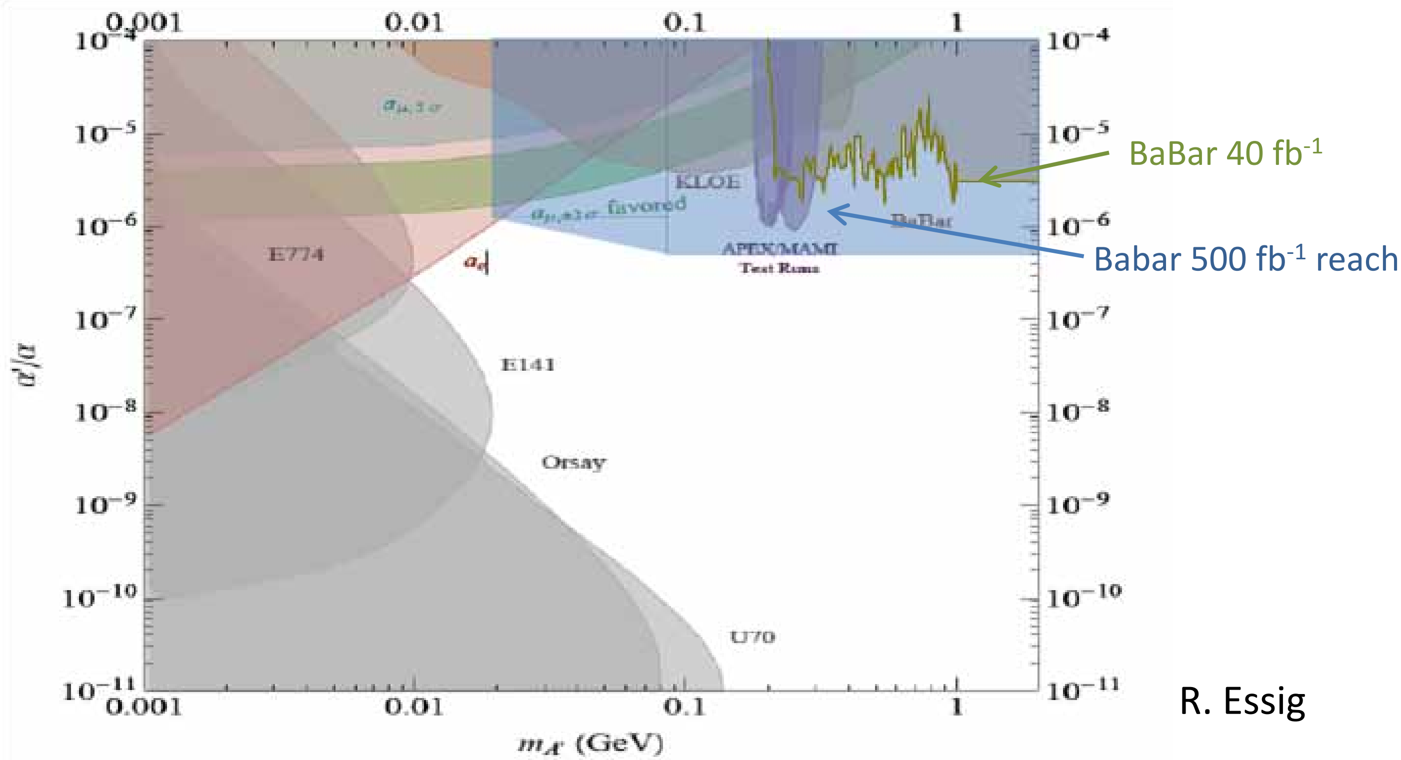
~470 $\times 10^6$ $\Upsilon(4S)$
~120 $\times 10^6$ $\Upsilon(3S)$ (10x BELLE)
~100 $\times 10^6$ $\Upsilon(2S)$ (10x CLEO)
~18 $\times 10^6$ $\Upsilon(1S)$ from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$

Summary of current A^0 BF upper limits from BaBar

reaction	Upper limit (10^{-5}) @ 90% CL	m_{A0} range (GeV/c^2)	Reference
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	0.026 - 0.83 ($\Upsilon(2S)$) 0.027 - 0.55 ($\Upsilon(3S)$)	0.212 – 9.3	PRL103, 081803 (2009)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	0.028 – 0.97	0.212 – 9.3	PRD87, 031102 (2013)
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	1.5 - 16	4.03 – 10.10	PRL103, 181801 (2009)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	0.9 – 13	3.6 – 9.2	arXiv:1210.5669 (2012)
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadr	0.1 – 8	0.3 – 7	PRL107, 221803 (2011)
$\Upsilon(1S) \to \gamma A^0, A^0 \to gg$	0.1 – 1000	0.5 – 9	PRD88, 031701 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to s\bar{s}$	1 – 100	0.5 – 9	PRD88, 031701 (2013)
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	0.07 – 3.1	3 – 7.6	arXiv:0808.0017 (2008)
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	0.19 – 0.45 0.27 – 37	0 – 8 8 – 9.2	PRL107, 021804 (2011)

Limits on dark photon searches at BaBar

- All searches for a light Higgs can be re-interpreted looking for a spin 1 A' boson in its $f\bar{f}$ decay



R. Essig

- Exclusion of almost all the "g-2 preferred" region